Comparison of the APS and UGIMAG Helmholtz Coil Systems

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ABSTRACT

UGIMAG [1] is manufacturing the NdFeB permanent magnet blocks to be used in undulator A now being assembled by STI Optronics. We would like to be able to compare measurements made at the plant with those made at ANL and potentially with those made at the STI facility. Since there are no permanent magnet standard samples, measurement systems are compared by trading sets of magnets set aside as standards. APS has ten NdFeB permanent magnet blocks supplied by Sumitomo [2] that we use to make these comparisons. These magnet samples have been extensively measured on the APS system. The data include the three vector components of the total magnetic dipole moment of the blocks as well as the spherical coordinates of the vector.

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Introduction

The Helmholtz coil technique measures the total magnetic moment of a permanent magnet block by measuring the integrated voltage induced in the coil as the magnet is moved in an established procedure. The theory is described in Ref. 4. At the APS, a procedure was developed that can measure the three vector components of the total magnetic moment. This procedure is being used at UGIMAG, Inc. in a system that duplicates the capabilities of the APS system by utilizing the measurement procedure and analysis methods developed here. The requirements for the permanent magnet blocks to be used in the undulators and wigglers include limits on the magnitude of the moment and on the error angle that the magnetic moment vector can have from the specified direction.

The UGIMAG staff were particularly interested in verifying the accuracy and repeatability of the angle measurements. In the past, it has been possible to routinely measure the main vector component to high precision and accuracy. The APS system was designed to achieve high precision and accuracy in the determination of the minor vector components along with the spherical-polar angles. The $2°$ limit on the error specified in the moment direction has been difficult to achieve primarily because it has not been possible to perform the measurement accurately at the magnet material manufacturer.

Data

All ten standard blocks have dimensions 3.5 cm$\times$3.3 cm$\times$1.7 cm. The volume is 19.635 cm^3 (1.1982 in^3). All are manufactured of NdFeB alloy with the easy axis of magnetization perpendicular to the large face of the block and one of the faces is marked to uniquely define the positive z–direction. The x–direction is parallel to the long dimension, the y–direction parallel to the mid-dimension, and the z–direction parallel to the short dimension. Six of the blocks have the magnetization pointing out of the marked face while the remaining four have magnetization in the reverse direction. All measurements reference the z–direction perpendicular to the back surface of the block. The ten standard blocks have been measured on the APS system [3]. The data is summarized in Table 1.

On April 1, 1994, the blocks were measured at the UGIMAG plant in the order shown in Table 2. Magnet N-1 was measured first and then again between each of the other blocks to act as a monitor of drift in the system and to demonstrate the repeatability of the measurements. In most of the cases, the temperature of block was measured after the magnetic measurement using a thermocouple.

Table 1: APS data from tests of ten standard blocks. The m represent the components and magnitude of the total magnetic moment in SI units.

Magnet ID	m_x [A m^2]	m_y [A m^2]	m_z [A m^2]	m [A m^2]	θ [deg]	ϕ [deg]	Temp. [C]
N–1	-0.2785	-0.1832	18.240	18.243	1.05	213.34	22.8
N–2	0.0829	0.7746	18.495	18.511	2.41	83.89	23.5
N–3	0.2037	-0.6498	18.133	18.146	2.15	287.41	23.8
S–4	0.0267	0.2893	-18.261	18.263	179.09	84.73	23.7
S–5	0.2373	0.8284	-18.247	18.268	177.30	74.02	23.9
EN–1	0.0413	0.5368	18.092	18.100	1.70	85.60	23.8
EN–2	0.0172	-0.5515	18.399	18.408	1.72	271.79	24.0
EN–3	0.0523	-0.1743	18.569	18.570	0.56	286.70	23.8
ES–4	-0.1860	0.6549	-18.261	18.274	177.86	105.86	23.9
ES–5	0.1086	0.3552	-18.743	18.746	178.86	73.00	23.9

Table 2: UGIMAG data from tests of ten standard blocks. The m represent the components of the magnetic moment in terms of the amplitude of the measured signal.

Meas. #	Magnet ID	Temp. [C]	m_x [arb]	m_y [arb]	m_z [arb]	m [arb]	θ [deg]	ϕ [deg]
1	N–1	22.8	-0.005319	-0.003555	0.3552	0.3553	1.03	213.76
2	N–1	—	-0.005398	-0.003688	0.3552	0.3552	1.05	214.34
3	N–2	23.5	0.003158	0.014957	0.3600	0.3603	2.43	78.08
4	N–1	24.3	-0.005400	-0.003674	0.3549	0.3550	1.05	214.23
5	N–3	23.3	0.002887	-0.012587	0.3531	0.3533	2.09	282.92
6	N–3	24.2	0.002869	-0.012599	0.3530	0.3533	2.10	282.83
7	N–1	24.5	-0.005398	-0.003682	0.3549	0.3550	1.06	214.30
8	S–4	24.0	0.001153	0.005693	-0.3552	0.3553	179.06	78.55
9	N–1	24.4	-0.005458	-0.003627	0.3548	0.3549	1.06	213.61
10	S–5	24.7	0.005301	0.016162	-0.3550	0.3554	177.26	71.84
11	N–1	24.9	-0.005472	-0.003615	0.3547	0.3548	1.06	213.45
12	EN–1	25.0	0.001396	0.010841	0.3522	0.3524	1.78	82.66
13	N–1	24.7	-0.005376	-0.003613	0.3547	0.3548	1.05	213.90
14	EN–2	25.3	0.000242	-0.011104	0.3581	0.3583	1.78	271.25
15	N–1	24.7	-0.005413	-0.003634	0.3546	0.3547	1.05	213.88
16	EN–3	25.6	0.000587	-0.003411	0.3614	0.3614	0.55	279.76
17	N–1	25.2	-0.005396	-0.003694	0.3546	0.3546	1.06	214.40
18	ES–4	25.5	-0.004131	0.012686	-0.3553	0.3555	177.85	108.04
19	N–1	—	-0.005463	-0.003647	0.3546	0.3547	1.06	213.73
20	N–1	25.2	-0.005452	-0.003704	0.3546	0.3547	1.06	214.19
21	ES–5	25.2	0.002061	0.006789	-0.3645	0.3645	178.88	73.11
22	N–1	—	-0.005375	-0.003647	0.3544	0.3545	1.05	214.16

Results

Figure 1 is a plot of the magnitude of the moment measured at APS compared to that measured at UGIMAG. We expect the data to be directly proportional if everything works well. As we can see, that is indeed the case. This is remarkable performance considering the strengths of the blocks vary a total of only 3.4%. The line in the figure is a least-squares fit assuming zero intercept.

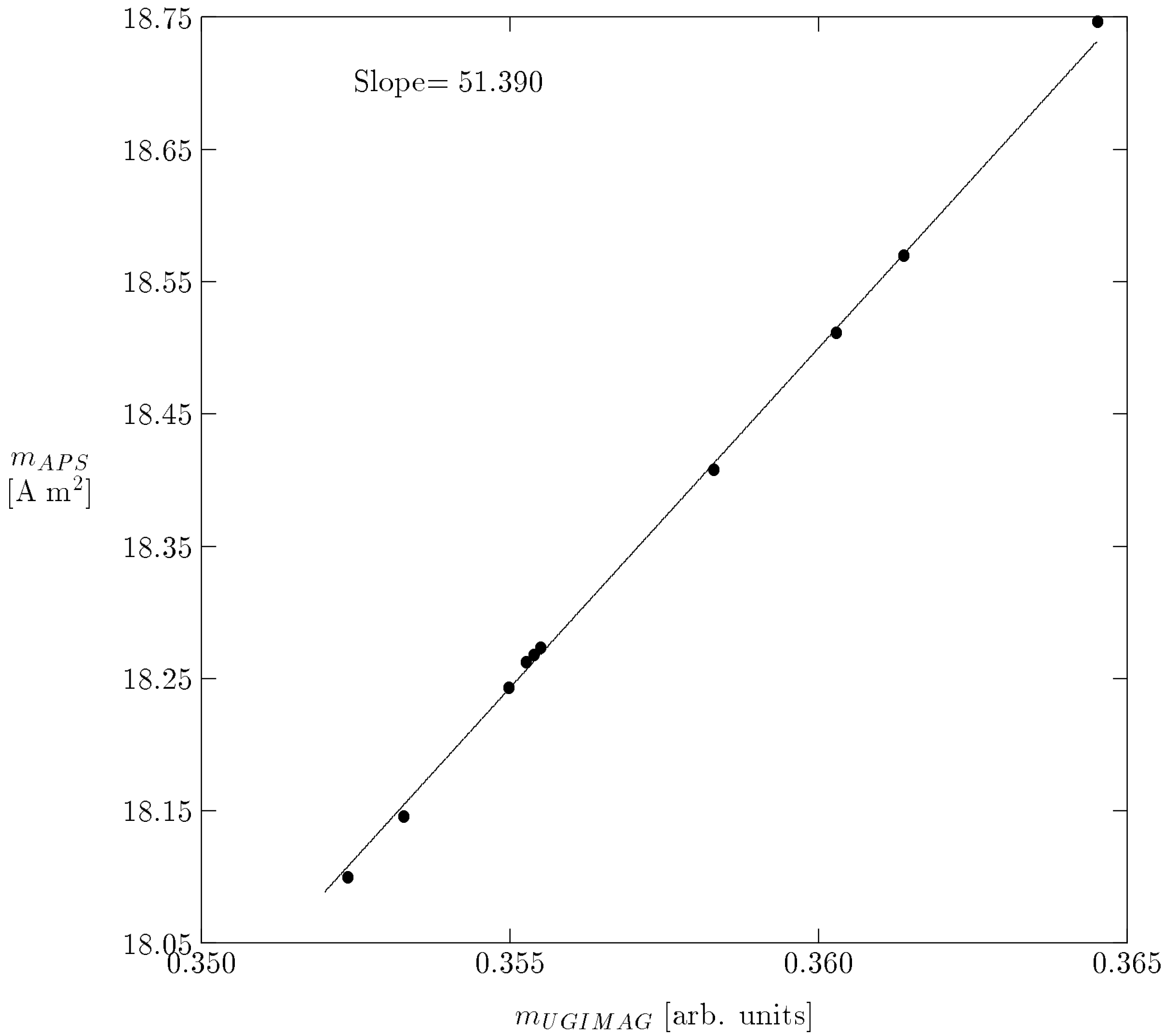

Figure 1: The magnitude of the total magnetic moment of the blocks is compared. The slope is of a line with zero intercept.

At UGIMAG, the results are interpreted in terms of the magnetization of the block in its open circuit environment.

$$4\pi M \text{ [kG]} = \frac{C\ D\ R}{V_{samp}} \equiv 10\mu_0 M \text{ [T]}. \tag{1}$$

C is the coil constant, D is the amplitude of the signal shown in the UGIMAG data tables with arbitrary units, R is the range on the integrating voltmeter and V_{samp} is the sample volume in in^3.

$$C = 0.02593 \tag{2a}$$
$$R = 1500 \tag{2b}$$

The result can be converted to SI units as shown by the equivalence and interpreted as the magnetic moment of the block. We may write the conversion factor from the signal to moment as

$$\frac{C\,R}{V_{samp}}\frac{1}{10}\left[\frac{\mathrm{T}}{\mathrm{kG}}\right]\frac{1}{\mu_0}V_{samp}. \tag{3}$$

In this confusing expression, we are converting from units used at the UGIMAG plant to the SI units used at APS. The first instance of V_{samp} has units in^3 while the second instance has units m^3. Let's call this factor K. It multiplies out to

$$K = 50.721 \tag{4}$$

with the result of multiplying the signal D by K having units Am^2. The slope of the fit to the plot of APS data as a function of the UGIMAG data for the magnitude of the moment is 51.390, about 1.3% higher than the calculated value of K.

These two slopes can now be used to compare magnitude data from the two systems. The 1.3% difference is not usually important in our applications. At a given site, the precision rather than the accuracy of the moment measurement is what is important. This factor may be used to make direct comparison of magnitude data from the two systems.

It is important to note that this correction factor has no effect on the determination of the spherical-polar angles. The calculation of these angles is independent of the absolute magnitude of the vector.

Our aim was to verify the accuracy of the angle measurements. Magnet sample N–1 was measured a total of twelve times. The data is displayed in Table 3. The angle θ has a total variation of only 0.03° with a standard deviation of 0.008°. This is a factor of three smaller than the design goal of the APS system and only slightly larger than that achieved by the APS system [3]. This is excellent performance.

The calculation of the azimuthal angle ϕ depends on the two small vector components. For this set of blocks, the x– and y–components are roughly two orders of magnitude smaller than the main z–component. These components are determined to the same absolute accuracy as the main component but because of the relative magnitude, have 100 times the relative error. This effect is worse when the polar angle approaches zero. Another side effect of using polar coordinates is that θ is always positive. Plotting a histogram of frequency as a function of θ will have a peak at some positive value with the distribution approaching zero as θ goes to zero. This makes it look like all blocks have an error angle with none being near "perfect." Another way to look at what is essentially a two-dimensional distribution is to use polar coordinates, treating θ as the radial coordinate and ϕ as the angle.

In previous work, the magnetic moment of the sample was corrected to a standard temperature. A part of the difference in the magnitudes observed is due to temperature

Table 3: UGIMAG repeatability data for sample N–1.

Meas. #	Temp. [C]	m_x [arb]	m_y [arb]	m_z [arb]	m [arb]	θ [deg]	ϕ [deg]
1	22.8	-0.005319	-0.003555	0.355231	0.355288	1.031797	213.756421
2	—	-0.005398	-0.003688	0.355169	0.355230	1.054326	214.340532
4	24.3	-0.005400	-0.003674	0.354926	0.354986	1.054164	214.231452
7	24.5	-0.005398	-0.003682	0.354855	0.354915	1.055055	214.293776
9	24.4	-0.005458	-0.003627	0.354805	0.354866	1.057998	213.607386
11	24.9	-0.005472	-0.003615	0.354739	0.354800	1.059138	213.448378
13	24.7	-0.005376	-0.003613	0.354711	0.354771	1.046082	213.904783
15	24.7	-0.005413	-0.003634	0.354612	0.354672	1.053323	213.877267
17	25.2	-0.005396	-0.003694	0.354575	0.354635	1.056516	214.396976
19	—	-0.005463	-0.003647	0.354646	0.354707	1.061099	213.725238
20	25.2	-0.005452	-0.003704	0.354610	0.354671	1.064785	214.191092
22	—	-0.005375	-0.003647	0.354437	0.354497	1.049909	214.156814
Average		-0.005410	-0.003648	0.354776	0.354836	1.053683	213.994176
Std Dev		0.000045	0.000043	0.000238	0.000238	0.008466	0.315006
% Error		-0.825896	-1.175309	0.067086	0.066955	0.803427	0.147203
Maximum		-0.005319	-0.003555	0.355231	0.355288	1.064785	214.396976
Minimum		-0.005472	-0.003704	0.354437	0.354497	1.031797	213.448378
Max-Min		0.000153	0.000149	0.000793	0.000791	0.032988	0.948598

effects. The average temperature in the UGIMAG laboratory was about 2°C higher than when measurements were made at APS. This would account for about 0.2% of the difference. An accurate correction and comparison is not possible in this case since neither thermometer was calibrated. In addition, the thermocouple used at UGIMAG was a type affected by magnetic fields. The temperature effects observed are real. The relative temperature changes observed are accurate. The absolute temperature measurements are not reliable.

Figure 2 shows the magnitude of the moment in arbitrary units plotted as a function of temperature. The line is a least-squares fit to the data. The slope implies a temperature coefficient of -0.076%/°C, a typical value for NdFeB-type magnet materials. The total temperature change is less than 3°C. The system can easily resolve the change in strength in the magnet.

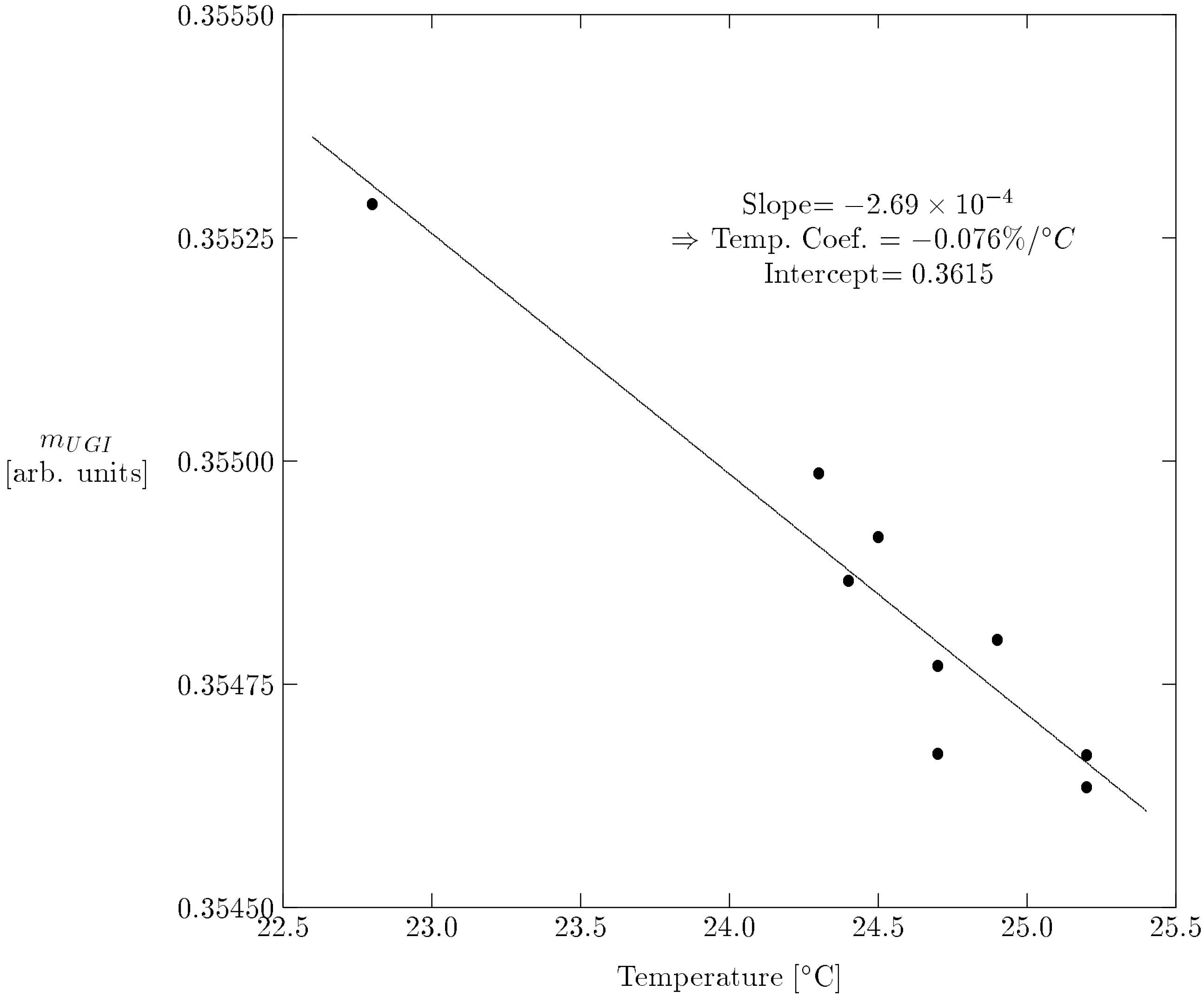

Figure 2: Sample N–1 was measured many times. The magnetic moment is a function of temperature as is apparent in this plot. The line is a least-squares fit. The slope of this line implies a temperature coefficient of -0.076%/°C, a typical value for NdFeB-type materials at room temperature.

Summary

The UGIMAG system is fully capable of measuring the polar angle and verify that it is less than 2°. Systems like the one designed at ANL/APS and duplicated at UGIMAG will enable us, in the near future, to tighten the specifications on permanent magnets and build ever more precise insertion devices.

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